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Studies of 'Salt' Scaling of Concrete

By

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Studies of "Salt" Scaling of Concrete

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The service record of air-entrained concrete pavements exposed to de-icing salts is excellent. However, the mechanism by which de-icers cause or accelerate surface scaling of non-air-entrained concrete is unknown. Furthermore, there is a not complete understanding of why entrained air is beneficial in this regard.

Although field experience indicates that air entrainment is a practical remedy for surface scaling, some laboratory tests indicate that under certain extremely severe conditions entrained air does not give complete protection.

The objective of this study is to provide more information on the effect of type and concentration of de-icer, curing condition of concrete, air entrainment, and other variables on the surface scaling of concrete. This information should lead to a better understanding of the effect of these variations and should be of assistance in the establishment of further remedial measures.

● THIS study comprised surface scaling tests of non-air-entrained and air-entrained concretes made with two different combinations of fine and coarse aggregate. The first is a manufactured trap rock sand and trap rock coarse aggregate from Dresser, Wisconsin; the second is a predominantly dolomitic natural sand from Elgin, Illinois, and a highly siliceous crushed natural gravel from Eau Claire, Wisconsin.

The concretes had cement contents of approximately 6 sacks per cu yd and slumps of 2½ to 3½ in. The maximum size of coarse aggregate was 1 in. The air-entrained concretes had air contents of about 7 percent, the top of the range of 4 to 7 percent which would normally be desirable for concretes with this maximum size of aggregate. It was anticipated that certain of the test procedures used might represent extremely severe exposure conditions and that a high inherent durability would be required in order to reveal more clearly differences in performance under these conditions. Some concretes at lower air contents were prepared for comparison.

Companion concrete specimens, after different preliminary curing procedures, were subjected to surface scaling tests using various concentrations of either calcium chloride, sodium chloride, ethyl alcohol, or urea as de-icers. Three different scale test procedures were used.

Materials

The cement used in these tests was a blend prepared from four different brands of Type I cements purchased in the Chicago area. Tables 1, 2, and 3 show the chemical composition, calculated potential compound composition, and the results of various physical tests of this Type I blend.

Two aggregate combinations were used. The first combination was a sand and crushed stone manufactured from a siliceous rock (trap rock) from Dresser, Wisconsin. The second combination consisted of a predominantly dolomitic natural sand from Elgin, Illinois, and a highly siliceous crushed gravel from Eau Claire, Wisconsin. Grading, specific gravity, absorption, and thermal coefficient of linear expansion for all aggregates are shown in Table 4. These aggregates have a good service record. The combination of completely manufactured aggregate was included in order to evaluate the influence of both natural and manufactured aggregates on the results of the scaling tests.

All aggregates were air dried and screened into various size fractions, six sizes for the fine aggregate and three for the coarse aggregate. When preparing a batch, the sizes were recombined to yield the gradings shown in Table 4. In order to provide a high degree of control over the total mixing water in a batch, the aggregates were weighed in the air-dried condition (moisture content known) and, 18 to 20 hours prior

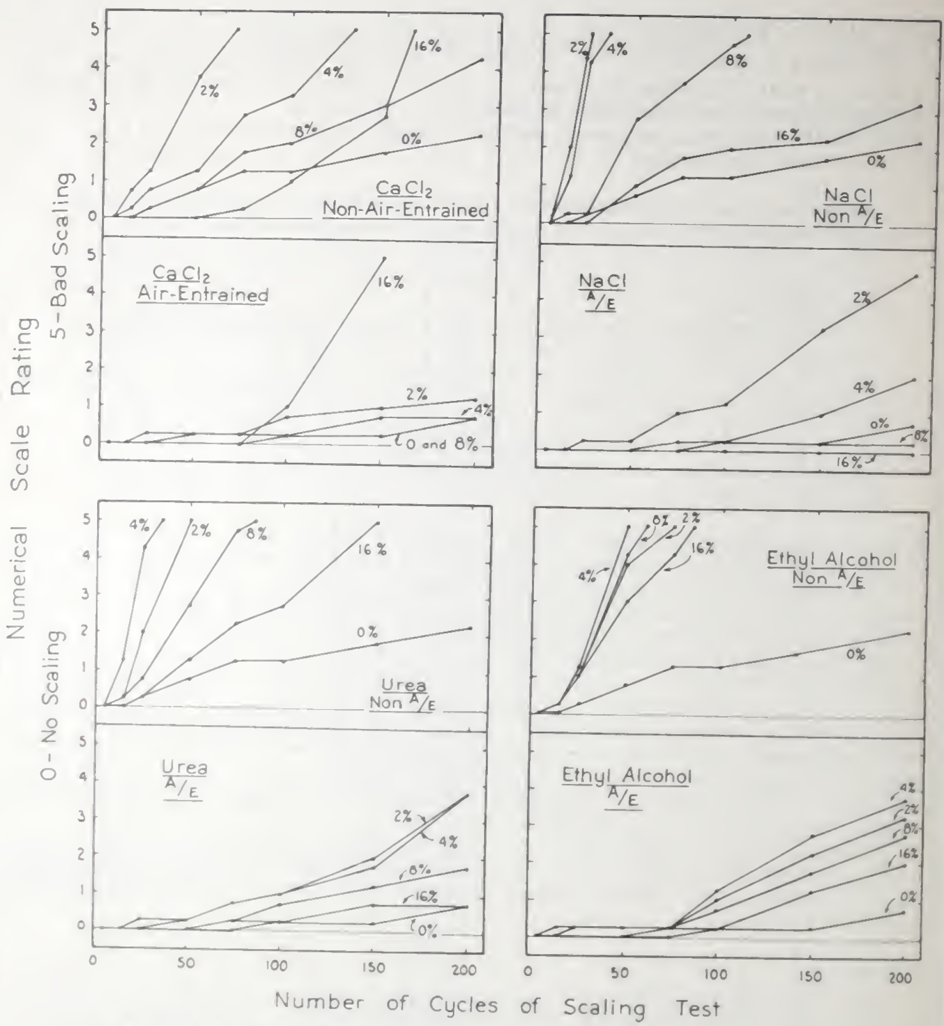

Figure 1. Effect of amount of de-icer on surface scaling on non-air-entrained and air-entrained concretes. Scale Test Procedure No. 2: Thaw solution refrozen on slab surface. Aggregates: Elgin, Illinois sand and Eau Claire, Wis. crushed gravel (1-in. top size) Specimens: 3 by 6 by 15-in. slabs cured continuously moist for 31 days prior to test. Cement Content: 6 sacks per cu yd. Slump: 2 1/2 to 3 1/2 in. Air Contents: Non A/E - 2.2 percent, A/E - 7.4 percent.

to use, inundated with a known amount of water. Excess water was drawn off and weighed immediately prior to mixing the concrete.

Neutralized Vinsol resin in solution was added at the mixer when preparing the air-entrained concrete.

The de-icers used in these scaling tests were commercial flake calcium chloride, sodium chloride, urea, and ethyl alcohol,

Fabrication of Specimens

Each batch contained 1.30 cu ft of concrete. Batches were mixed for $2\frac{1}{2}$ minutes in an open-tub mixer of $1\frac{3}{4}$-cu ft capacity. A slump test and an air content determination by the pressure method were made on each batch of concrete.

Generally, two specimens were made for a particular test condition. In a few cases, three specimens were made. In all cases, these companion specimens were made on different days.

The specimens used in the scaling test were slabs 3 in. in depth and 6 by 15 in. in area. These slabs were cast in watertight steel molds, the molds were filled in two

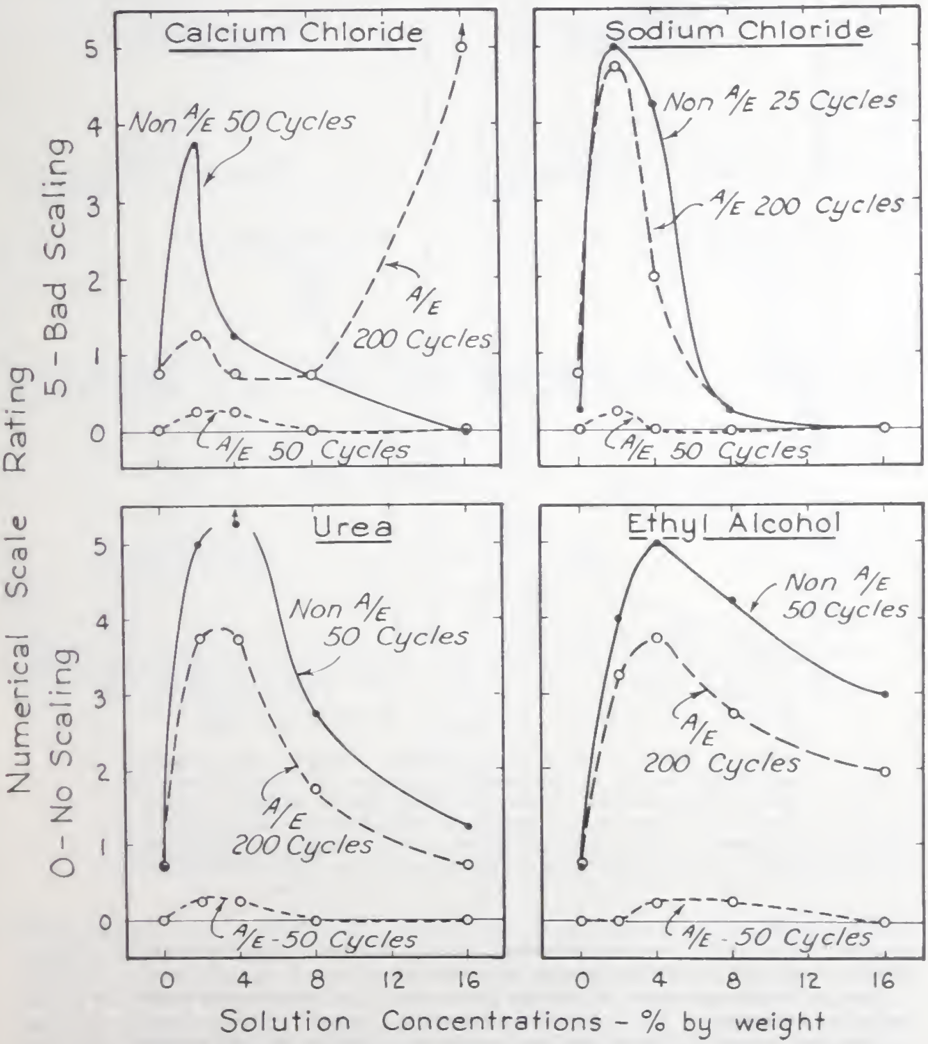

Figure 2. Effect of amount of de-icer on surface scaling (test procedure No. 2 - thaw solution refrozen).

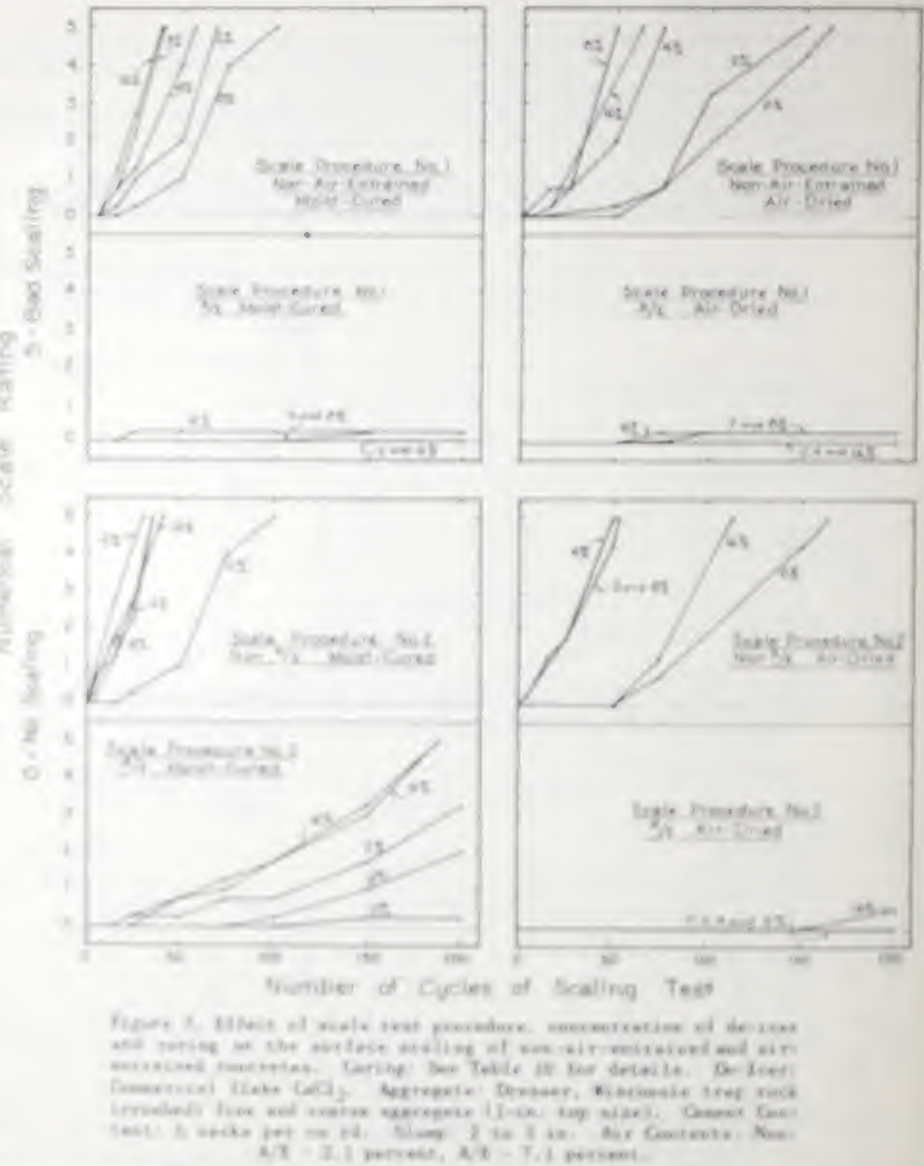

Figure 3. Effect of scale test procedure, concentration of de-icer and curing on the surface scaling of non-air-entrained and air-entrained concretes. Curing: See Table III for details. De-Icer: Commercial flake $CaCl_2$. Aggregate: Dresser, Wisconsin trap rock (crushed) fine and coarse aggregate (1-in. top size). Cement Content: 5 sacks per cu yd. Slump: 2 to 3 in. Air Contents: Non-A/E = 2.1 percent, A/E = 7.1 percent.

layers of equal depth, and each layer was rodded 50 times with a ⅝-in. diameter hemi-spherical tip tamper. Immediately after casting, the surface was given a final finish with a wood float, and the specimens were then covered with two thicknesses of damp burlap (not in contact with surface) and a tarpaulin. At the age of 20 to 24 hours, the molds were stripped. The slabs were equipped with an air-entrained mortar dike (approximately ¾ by ¾ in. in section) around the edges of the finished surface, and then the slabs were placed in the moistroom.

Curing Conditions

Companion specimens were subjected to two different sets of curing conditions:

1. Continuously moist cured at 73 deg F for 28 days, followed by an additional 3 days in the moistroom with the surface of the slab covered with water $\frac{1}{4}$ in. in depth. These will be referred to hereafter as moist cured.

2. Continuously moist cured at 73 deg F for 14 days, then 14 days in the air of the laboratory at 73 deg F and 50 percent relative humidity, followed by an additional 3

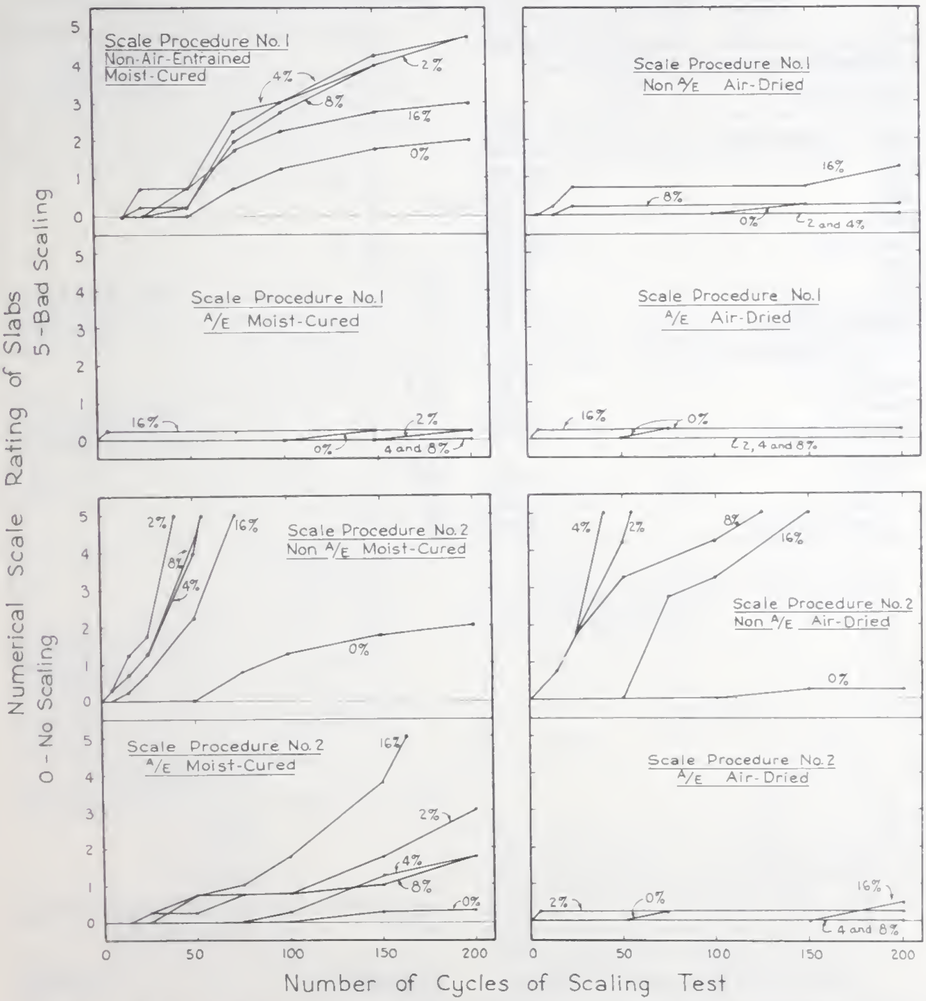

Figure 4. Effect of scale test procedure, concentration of de-icer and curing on the surface scaling of non-air-entrained and air-entrained concretes. Curing: See Table 9 for details. De-Icer: Commercial flake $CaCl_2$. Aggregate: Elgin, Illinois sand and Eau Claire, Wis. crushed gravel (1-in. top size). Cement Content: 6 sacks per cu yd. Slump: 2 to 3 in. Air Contents: Non-A/E - 2.2 percent, A/E - 7.1 percent.

days in air with the surface of the slab covered with water ¼ in. in depth. These will be referred to hereafter as air dried.

Test Methods

Three different procedures were followed in determining the surface scaling resulting from the application of different deicers:

Procedure 1. After freezing 250 ml of water on the surface of a concrete slab

TABLE 1

CHEMICAL COMPOSITION OF TYPE I BLEND

PCA Lot No. 18681. Blend of equal parts by weight of four Type I cements purchased locally.

Major Components	%
SiO_2	20.66
Al_2O_3	5.89
Fe_2O_3	2.84
Total CaO	62.90
MgO	2.96
SO_3	2.16
Ignition Loss	1.58
Minor Components	**%**
Mn_2O_3	0.28
Free CaO	1.09
Insoluble Residue	0.18
Alkalies:	
Na_2O	0.20
K_2O	0.54
Total as Na_2O	0.56

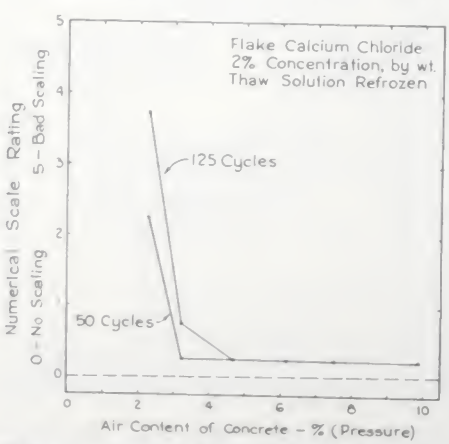

Figure 6. Effect of entrained air on resistance to surface scaling (scale test prodedure No. 2). Aggregates: Elgin, Ill. sand and Eau Claire, Wis. gravel. Cement Content: 6 sacks per cu yd. Slump: 3 in. Curing: 14 days moist, 14 days in air plus 3 days in air with water on top surface.

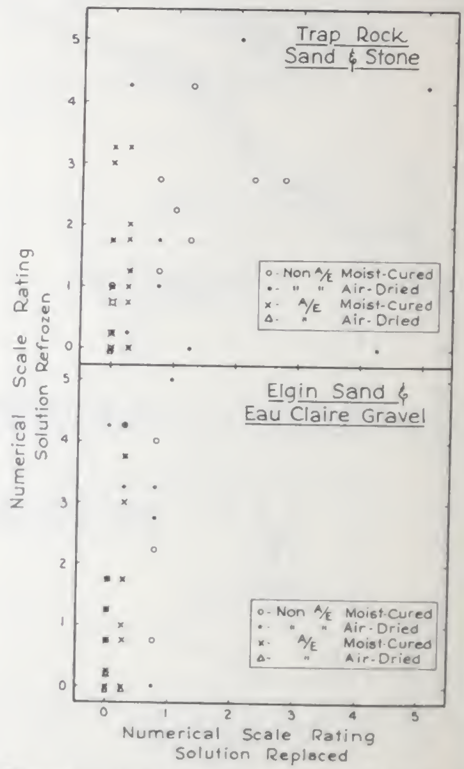

Figure 5. Comparison of scale test procedures.

TABLE 2

POTENTIAL COMPOUND COMPOSITION OF CEMENT

Compound	% by Wt
C_3S	44.8
C_2S	25.4
C_3A	10.8
C_4AF	8.7
$CaSO_4$	3.67
Free CaO	1.09

in a room maintained at -20 deg F, the slab was removed to a room maintained at 70 deg F and de-icer was applied immediately to the ice. After thawing, the resulting solution was removed, the surface was rinsed and 250 ml of water was placed on the surface for the next freeze portion of the cycle. The total time in freezer was approximately 18 hours. The total time in the thawing room was approximately 6 hours.

Procedure 2. The same conditions existed as in No. 1 except that the particular solution of de-icer and water was kept on the specimen during both the freeze and thaw portions of the cycle.

TABLE 3

MISCELLANEOUS PHYSICAL TESTS OF CEMENT

Tests made in accordance with ASTM Standards current in December, 1951 (specific gravity determined in water rather than kerosene).

Specific surface, sq cm per gram	
Wagner	1710
Blaine	3310
Passing No. 325-mesh, %	91.1
Specific gravity, in water	3.182
Normal consistency, %	24.5
Time of setting: Vicat	
Initial	3 hr 15 min
Final	6 hr 20 min
Gillmore	
Initial	4 hr 20 min
Final	6 hr 30 min
Autoclave expansion, %	0.135
Air content, 1-4 standard mortar, %	8.2

TABLE 4

DATA ON AGGREGATES

Fine Aggregate										
Source and Type	% Retained on Sieve No. Indicated						Fineness Modulus	Bulk Sp Gr, S. S. D.[a]	24-Hr Absorption, % by Wt	Mean Linear Thermal Coeff of Expansion,[b] $x10^6/^oF$
	4	8	16	30	50	100				
Dresser, Wis (crushed)	0	5	30	55	80	92	2.62	2.918	1.14	4.74
Elgin, Ill. (natural)	0	18	33	57	87	95	2.90	2.645	2.25	5.73

Coarse Aggregate							
Source and Type	% Retained on Sieve Indicated				Bulk Sp Gr, S. S. D.[a]	24-Hr Absorption, % by Wt	Mean Linear Thermal Coeff of Expansion,[b] $x10^6/^oF$
	1-in.	3/4-in.	3/8-in.	No. 4			
Dresser, Wis (crushed)	0	25	70	100	2.980	0.20	4.74
Eau Claire, Wis (natural)	0	25	70	100	2.693	1.33	5.94

[a] Saturated, surface-dry.
[b] Dilatometer method.

TABLE 5

CONCRETE MIX DATA

Cement	Cement Content, sacks per cu yd	Net W/C, gal. per sack	% Sand, Abs Volume	Slump in.	Air Content, % (pressure)
Dresser, Wis Fine and Coarse Aggregate (Crushed)					
Type I	6.0	7.2	46	2.2	2.1
Type I + Vinsol Resin	5.8	6.9	42	3.0	7.1
Elgin, Ill. Fine Aggregate and Eau Claire, Wis Coarse Aggregate (Natural)					
Type I	6.0	5.2	41	3.2	2.2
Type I + Vinsol Resin	6.0	4.8	36	3.3	7.2

The sodium chloride, calcium chloride, and urea solutions were replaced with fresh solutions once each week. The ethyl alcohol solutions were replaced twice each week.

Procedure 3. In this procedure, the specimen was frozen with the surface damp (no excess water). On removal to the thawing room, the surface was covered with 250 ml of solution containing the particular amount and type of de-icer required. After completion of thawing, the solution was removed, and the surface was rinsed and drained completely for the next freeze portion of the cycle.

TABLE 6

RESULTS OF SCALING TESTS WITH DIFFERENT DE-ICERS

Scale Test: Thaw solution refrozen (Procedure 2)
Specimens: 3- by 6- by 15-in. slabs cured continuously moist for 31 days prior to start of test
Cement Content: 6 sacks per cu yd, $2\frac{1}{2}$ to $3\frac{1}{2}$-in. slump
Aggregates: Elgin, Illinois sand and Eau Claire, Wisconsin gravel (1-in. top size)
Air Contents: Non-A/E - 2.2%, A/E - 7.4%

Concentration of Soln after Thawing, % by Wt	Numerical Scale Rating at Indicated Number of Cycles															
	Non-Air-Entrained Concrete								Air-Entrained Concrete							
	5	15	25	50	75	100	150	200	5	15	25	50	75	100	150	200
No De-Icer																
0	0	0	0+	1-	1+	1+	2-	2+	0	0	0	0	0	0+	0+	1-
Flake Calcium Chloride																
2	0	1-	1+	4-	(70)[a]				0	0	0+	0+	0+	1-	1	1+
4	0	0+	1-	1+	3-	3+	(133)		0	0	0	0+	0+	0+	1-	1-
8	0	0	0+	1-	2-	2	3	4+	0	0	0	0	0	0+	0+	1-
16	0	0	0	0	0+	1	3-	(164)	0	0	0	0	0	1	(150)	
Sodium Chloride																
2	0	2	(25)						0	0	0+	0+	1	1+	3+	5-
4	0	1+	4+	(35)					0	0	0	0	0+	0+	1	2
8	0	0+	0+	3-	4-	5-	(108)		0	0	0	0	0+	0+	0+	0+
16	0	0	0	1	2-	2	2+	3+	0	0	0	0	0	0	0	0
Urea																
2	0	0+	2	(50)					0	0	0+	0+	1-	1	2	4-
4	0	1-	3	(35)					0	0	0	0+	1-	1	2-	4-
8	0	0+	1-	3-	5-	(85)			0	0	0	0	0+	1-	1+	2-
16	0	0	0+	1+	2+	3-	(150)		0	0	0	0	0+	0+	1-	1-
Ethyl Alcohol																
2	0	0+	1+	4	(75)				0	0	0	0	0+	1	2+	3-
4	0	0+	1+	(50)					0	0+	0+	0+	0+	1+	3-	4-
8	0	0+	1	4+	(60)				0	0	0+	0+	0+	1-	2-	3-
16	0	0+	1	3	4+	(85)			0	0	0	0	0+	0+	1+	2

[a] ( ) - Number of cycles at which test was discontinued at a rating of 5.

The following listing shows which de-icers and which concretes were used in these three procedures:

Procedure 1 - Calcium Chloride
- Both aggregate combinations
- Non-air-entrained and air-entrained
- Both curing conditions

Procedure 2 - Calcium Chloride
- Both aggregate combinations
- Non-air-entrained and air-entrained
- Both curing conditions

Sodium Chloride, Urea, and Ethyl Alcohol
- Elgin sand and Eau Claire gravel
- Non-air-entrained and air-entrained
- Moist-cured concretes only

Procedure 3 - Calcium Chloride
- Dresser trap rock sand and coarse aggregate
- Non-air-entrained
- Both curing conditions

At intervals during the scaling test, the surfaces were examined carefully, rated as to extent and depth of scale and assigned a numerical rating as follows: 0 - no scaling, 1 - very slight scaling, 2 - slight to moderate scaling, 3 - moderate scaling, 4 - moderate to severe scaling, and 5 - severe scaling.

TABLE 7

RESULTS OF SCALING TESTS - TRAP ROCK FINE AND COARSE AGGREGATE

Specimens: 3- by 6- by 15-in. slabs De-Icer: Flake calcium chloride
Curing: (a) 31 days moist (b) 14 days moist, 14 days in air plus 3 days in air with water on surface
Cement Content: 6 sacks per cu yd, 2 to 3 in. slump
Aggregates: Dresser, Wis. trap rock fine and coarse aggregate (1-in. top size)
Air Content: Non-A/E - 2.1%, A/E - 7.1%

Concentration of Soln after Thawing % by Wt	Numerical Scale Rating at Indicated Number of Cycles: Thaw Solution Replaced (Procedure 1)								Thaw Solution Refrozen (Procedure 2)							
	5	15	25	50	75	100	150	200	5	15	25	50	75	100	150	200
Non-Air-Entrained - Moist Cured																
0	0	0	0+	1	4	(100)[a]			-	-	-	-	-	-	-	-
2	0	0+	1	2	(68)				1-	1+	2+	(35)				
3	0	1-	1	3	(68)				-	-	-	-	-	-	-	-
4	0	1-	1+	4	(57)				1	3-	4+	(30)				
6	0	1-	2	(43)					-	-	-	-	-	-	-	-
8	0	1-	2+	(40)					0+	1+	3-	(35)				
10	0	1+	2+	(39)					-	-	-	-	-	-	-	-
16	0	1+	3-	(39)					0	2-	3-	(40)				
Non-Air-Entrained - Air Dried																
0	0	0	0	0	1-	2	4+	(163)	-	-	-	-	-	-	-	-
2	0	0	0	0+	1-	3+	(150)		0+	1	2-	4+	(53)			
3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	0	0+	1-	2	(75)				0+	1+	2-	(50)				
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	0+	1-	1-	(50)					0+	1	2-	4+	(53)			
10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	0	0+	1+	4-	(63)				0	0	0	0	1+	4-	(113)	
Air-Entrained - Moist Cured																
0	0	0	0	0	0	0	0+	0+	-	-	-	-	-	-	-	-
2	0	0	0	0	0	0	0	0	0	0	0+	0+	1-	1-	2-	3+
3	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-
4	0	0	0	0	0	0	0	0	0	0	0+	1-	1	2-	3	(188)
6	0	0	0	0	0	0	0	0+	-	-	-	-	-	-	-	-
8	0	0	0	0	0	0	0+	0+	0	0	0	0	0	0+	1	2
10	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-
16	0	0	0+	0+	0+	0+	0+	0+	0	0	0	1-	1+	2-	3+	(188)
Air-Entrained - Air Dried																
0	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-
2	0	0	0	0	0	0+	0+	0+	0	0	0	0	0	0	0	0
3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	0	0	0	0	0+	0+	0+	0+	0	0	0	0	0	0	0	0
10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0[b]

[a] ( ) - Number of cycles at which test was discontinued at a rating of 5.
[b] At 325 cycles entire surface scaled off abruptly as a layer about 1/16 in. thick.

TABLE 8

RESULTS OF SCALING TESTS - ELGIN SAND AND EAU CLAIRE GRAVEL

Specimens: 3- by 6- by 15-in. slabs De-Icer: Flake calcium chloride
Curing: (a) 31 days moist (b) 14 days moist, 14 days in air plus 3 days in air with water on surface
Cement Content: 6 sacks per cu yd, 2- to 3-in. slump
Aggregates: Elgin, Ill. sand and Eau Claire, Wis. crushed gravel (1-in. top size)
Air Content: Non-A/E - 2.2%, A/E - 7.1%

Concentration of Soln after Thawing	Numerical Scale Rating at Indicated Number of Cycles															
	Thaw Solution Replaced (Procedure 1)								Thaw Solution Refrozen (Procedure 2)							
% by Wt	5	15	25	50	75	100	150	200	5	15	25	50	75	100	150	200
							Non-Air-Entrained - Moist Cured									
0	0	0	0	0	1-	1+	2-	2	-	-	-	-	-	-	-	-
2	0	0	0	0+	2+	3	4	5-	0+	1+	2-	(40)				
3	0	0	0	0+	2-	3-	4	5-	-	-	-	-	-	-	-	-
4	0	0	0	1-	3-	3	4+	5-	0+	1-	1+	4	(55)			
6	0	0	0+	0+	3-	4-	(138)[a]		-	-	-	-	-	-	-	-
8	0	0	0+	0+	2	3-	4	5-	0+	1-	1+	4+	(55)			
10	0	0	1-	1-	2+	3-	4	5-	-	-	-	-	-	-	-	-
16	0	0	1-	1-	2-	2+	3-	3	0	0+	1-	2+	(72)			
							Non-Air-Entrained - Air Dried									
0	0	0	0	0	0	0	0+	0+	-	-	-	-	-	-	-	-
2	0	0	0	0	0	0	0	0	0+	1-	2-	4+	(55)			
3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	0	0	0	0	0	0	0	0	0+	1-	2-	(40)				
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	0	0	0+	0+	0+	0+	0+	0+	0+	1-	2-	3+	4-	4+	(125)	
10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	0	0+	1-	1-	1-	1-	1	1+	0	0	0	0	3-	3+	(150)	
							Air-Entrained - Moist Cured									
0	0	0	0	0	0	0	0+	0+	-	-	-	-	-	-	-	-
2	0	0	0	0	0	0	0	0+	0	0	0+	0+	1-	1-	2-	3
3	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0+	1+	2-
6	0	0	0	0	0	0	0	0+	-	-	-	-	-	-	-	-
8	0	0	0	0	0	0	0	0	0	0	0+	1-	1-	1-	1	2-
10	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-
16	0+	0+	0+	0+	0+	0+	0+	0+	0	0	0	1-	1	2-	4-	(163)
							Air-Entrained - Air Dried									
0	0	0	0	0	0+	0+	0+	0+	-	-	-	-	-	-	-	-
2	0	0	0	0	0	0	0	0	0+	0+	0+	0+	0+	0+	0+	0+
3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	0+	0+	0+	0+	0+	0+	0+	0+	0	0	0	0	0	0	0	0[b]

[a] ( ) - Number of cycles at which test was discontinued at a rating of 5.
[b] Surface shell scaled off, about 1/16-in. thick. Discontinued at 237 cycles.

TABLE 9

RESULTS OF SCALING TESTS - TRAP ROCK FINE AND COARSE AGGREGATES

Test Cycle: Slabs frozen with surface damp (no excess of water). Thaw solution placed directly on surface at start of thawing period (Procedure 3).
Specimens: 3- by 6- by 15-in. slabs. De-Icer: Flake calcium chloride.
Curing: (a) 31 days moist. (b) 14 days moist, 14 days in air plus 3 days in air with water on surface.
Cement Content: 6 sacks per cu yd, 2- to 3-in. slump, non-air-entrained.
Aggregates: Dresser, Wisconsin, trap rock fine and coarse aggregates (1-in. top size).
Air Content: 2.1%

Concentration of Thaw Solution % by Wt	Numerical Scale Rating at Indicated Number of Cycles									
	25	50	75	100	150	25	50	75	100	150
0	0	0	0	0	0	0	0	0	0	0
2	0+	0+	0+	0+	0+	0	0	0	0	0
4	0+	0+	0+	0+	0+	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0

DISCUSSION OF RESULTS

Effect of Concentration of Different De-Icers on Scale Resistance

The work of Arnfelt[1] has indicated that concretes frozen and thawed while immersed in solutions of different materials showed maximum deterioration at relatively low solution concentrations and that further increase in concentration resulted in a decrease in deterioration. Field observations in this country appeared to indicate that scaling of concrete pavements increased with increase in the amount of calcium chloride or rock salt used as de-icers.

Before making a general attack on the problem of surface scaling, it was desirable to substantiate Arnfelt's work using four materials as de-icers: calcium chloride, sodium chloride, urea, and ethyl alcohol. The concretes used in this portion of the study were made with the Elgin sand and Eau Claire gravel. Further information on these concretes is shown in Table 5.

These concretes were moist cured prior to test. Scale test Procedure 2 was used to simulate in some respects Arnfelt's tests in which the concretes were frozen and thawed while immersed in the solution. In Procedure 2, the solution of water and de-icer remained on the surface of the specimen during both the freeze and thaw portions of the cycle.

Table 6 and Figure 1 show the effect of concentration of solution on the scale resistance of these concretes. The non-air-entrained concretes show severe scaling much sooner than the air-entrained concretes, with the rate of scaling much greater at solution concentrations of 2 and 4 percent than at 0, 8, and 16 percent. These data confirm the observations of Arnfelt. Figure 2 shows more clearly the greater amounts of surface scaling occurring with the intermediate and relatively low concentrations of de-icers.

These data are important with regard to the mechanism by which scaling occurs. The opinion advanced most frequently is that the mechanism is primarily a chemical attack. If this were true, surface scaling would be expected to increase with an increase in concentration of de-icer. These tests show that this is not so. In addition, the de-icers used in these tests are dissimilar chemically. It appears, therefore, that the mechanism producing surface scaling is primarily physical.

Effect of Test Procedure on Scale Resistance

Tables 7 and 8 show the results of scaling tests of non-air-entrained and air-entrained concretes made with the Dresser trap rock aggregate and the Elgin sand and Eau Claire gravel, using both Procedure 1 and 2 and calcium chloride as the de-icer. In Procedure 1 the thaw solution is replaced with fresh water for the freeze portion of the cycle; in Pro-

[1] "Damage on Concrete Pavements by Wintertime Salt Treatment," Arnfelt, Harry, Meddelande 66, Statens Vaginstitut, Stockholm, 1943.

TABLE 10

RESULTS OF SCALING TESTS - ELGIN SAND AND EAU CLAIRE GRAVEL

Scale Test: Thaw solution refrozen (Procedure 2).
De-Icer: Flake calcium chloride, 2% solution concentration (by weight).
Specimens: 3- by 6- by 15-in. slabs cured 14 days moist, 14 days in air plus 3 days in air with water on surface.
Cement Content: 6 sacks per cu yd, 3-in. slump.
Aggregates: Elgin, Illinois sand and Eau Claire, Wisconsin gravel (1-in. top size).
Air Content: Agent added at mixer to produce range in air contents shown.

Air Content of Concrete %	Numerical Scale Rating at Indicated Number of Cycles						
	5	15	25	50	75	100	125
2.3	1-	1	2-	2+	3+	3+	4-
3.2	0+	0+	0+	0+	1-	1-	1-
4.7	0+	0+	0+	0+	0+	0+	0+
6.2	0	0	0+	0+	0+	0+	0+
7.5	0	0	0	0	0+	0+	0+
9.9	0	0	0+	0+	0+	0+	0+

cedure 2 the thaw solution is refrozen. Companion concretes were cured continuously moist or moist plus a period of air drying prior to test.

Figures 3 and 4 show the numerical scale ratings as a function of the calcium chloride solution concentration for these concretes and test procedures during 200 cycles of test. Where scaling has developed, note that, in general, the more severe scaling occurs at some intermediate and relatively low solution concentration. The scaling which occurs when the thaw solution is refrozen is generally more severe than when the solution is replaced. The usual laboratory procedure of replacing the thaw solution with fresh water (Procedure 1) apparently does not represent the most severe exposure attainable. For the purpose of determining the scale resistance for the most severe exposure conditions, the laboratory test should involve refreezing the thaw solution (Procedure 2). There appears to be no general relationship between the scaling produced by Procedures 1 and 2. Figure 5 shows only that Procedure 2 is generally much more severe than Procedure 1.

Some non-air-entrained concretes, both moist cured and air dried, made with the Dresser trap rock aggregate were tested for scale resistance using Procedure 3. The results are shown in Table 9. In test Procedure 3 the concrete specimen is frozen with the surface damp (no excess water) and the surface is then thawed with the appropriate calcium chloride solution. The scale ratings obtained during 150 cycles of test are shown in Table 9. No scaling has developed on any of these concretes exposed to calcium chloride solutions concentrations ranging from 0 to 16 percent, except for some very slight scale on the moist cured concretes exposed to the 2 and 4 percent solution concentrations. These very same concretes would have scaled rapidly under the test conditions of Procedure 1 and 2. It would appear that the scale resistance of the surface was enhanced by the rapid drying of the top surface of the slab, such as would occur when a warm wet specimen is placed in cold atmosphere having a low moisture content.

Effect of Prior Curing on Scale Resistance

Pavements rarely obtain curing comparable to continuous moist curing in the laboratory. Generally, after a minimum prescribed curing period, the concrete is exposed to drying conditions with subsequent rewetting at intervals by rainfall. On rewetting, however, the amount of water reabsorbed rarely equals that lost during the drying period, unless the period of wetting is exceptionally long. This results in a lowered degree of saturation.

The effect on scale resistance of continuous moist curing and a curing period comprised of both moist curing and air drying is shown in Figures 3 and 4. In almost all instances, continuous moist curing resulted in concrete surfaces less resistant to surface scaling than the concretes which underwent some air drying prior to test. For the non-air-entrained concretes, although the period of air drying reduced the amount of scaling, the resistance of the surfaces was not satisfactory, with the exception of the air-dried concrete made with the Eau Claire aggregate which was tested for scale resistance by Procedure 1, replacing the thaw solution with fresh water.

The air-dried air-entrained concretes made with both combinations of aggregates showed only very slight scaling during 200 cycles of Procedure 1 or 2. Despite the severity of Procedure 2, the period of air drying of the air-entrained concretes produced concretes resistant to 200 cycles of this test procedure. Concrete pavements may sometimes be subjected simultaneously to conditions of exposure similar to that of Procedure 2 and to low de-icer concentrations. Despite this particularly severe combination of exposure conditions, air-entrained concrete pavements have an excellent performance record, which may in part be the result of periodic air drying of the pavement surface. Laboratory tests should therefore include tests on air-dried concretes.

Effect of Amount of Air on Scale Resistance

From over-all durability considerations, the desired air content for concretes made with aggregate of 1-in. maximum size is in the range of 4 to 7 percent based on previous laboratory tests and field experience. The air-entrained concretes used in this

study had air contents near the upper limit of this range, since preliminary tests had indicated that a combination of continuous moist curing followed by exposure to low de-icer concentrations in scale test Procedure 2 (thaw solution refrozen) was an extremely severe test. Additional concretes were prepared in order to evaluate the scale resistance at various air contents within this range. Figure 6 shows some of these data which indicate that the concretes with 4. 7 percent air content showed surface scale ranging from none to very slight as evidenced by a scale rating of 0+ at 125 cycles. For concretes cured and tested in the same manner (see Table 8) and made with the same aggregate and an air content of 7. 1 percent, the scale rating at 125 cycles was identical. This indicates that an air content at the middle of the recommended range of 4 to 7 percent for this type of concrete performed as well as the concrete with 7. 1 percent air content. Further details of these tests are shown in Table 10.

SUMMARY AND CONCLUSIONS

These laboratory tests provide new information on the effect of de-icers on the surface scaling of non-air-entrained and air-entrained concretes, each made with two different coarse aggregates, cured differently, and tested under a variety of scale test procedures. While these tests did not provide data from which a complete concept of the mechanism involved can be drawn, they have provided a basis for further study, some of which is already under way.

Based on these laboratory tests, the following statements appear valid:

1. Chemically dissimilar materials, inorganic or organic, salts or non-salts, which function as de-icers also cause "salt" scaling, which more appropriately should be called "de-icer scaling."
2. Relatively low concentrations (of the order of 2 to 4 percent by weight) of de-icer produce more surface scaling than higher concentrations or the absence of de-icer.
3. On the basis of the foregoing, it appears that the mechanism of surface scaling is primarily physical rather than chemical.
4. Surface scale test procedures greatly influence the rate of scaling. The most severe test procedure yet discovered is one in which the concrete is alternately frozen and thawed with the de-icer solution remaining on the top surface of the concrete rather than being replaced with fresh water prior to each freezing.
5. No scaling was produced when the concrete surface had no free water on it during the freeze portion of the cycle.
6. A period of air drying of the concretes prior to the start of scaling tests increased the resistance to surface scaling. Air-entrained concretes treated in this manner were immune to the most severe scale test procedure for more than 200 cycles of test.
7. With the fixed cement content and slump as specified by these tests, the concrete made with the Elgin sand and Eau Claire gravel showed more resistance to surface scaling than the concretes made with the Dresser trap rock fine and coarse aggregate.